International Journal of Machine Tools & Manufacture 87 (2014) 89–95

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

journal homepage: www.elsevier.com/locate/ijmactool

Validation of volumetric error compensation for a five-axis machine using surface mismatch producing tests and on-machine touch probing

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ARTICLE INFO

Article history:
Received 17 May 2014
Received in revised form
30 July 2014
Accepted 4 August 2014
Available online 12 August 2014

Keywords:
Error compensation validation
Surface mismatch
On-machine probing
Five-axis machining

ABSTRACT

In order to validate volumetric error compensation methods for five-axis machine tools, the machining of test parts has been proposed. For such tests, a coordinate measuring machine (CMM) or other external measurement, outside of the machine tool, is required to measure the accuracy of the machined part. In this paper, a series of machining tests are proposed to validate a compensation strategy and compare the machining accuracy before and after the compensation using only on-machine measurements. The basis of the tests is to machine slots, each completed using two different rotary axes indexations of the CNC machine tool. Using directional derivatives of the volumetric errors, it is possible to verify that a surface mismatch is produced between the two halves of the same slot in the presence of specific machine geometric errors. The mismatch at the both sides of the slot, which materializes the machine volumetric errors is measured using touch probing by the erroneous machine itself and with high accuracy since the measurement of both slot halves can be conducted using a single set of rotary axes indexation and in a volumetric region of a few millimetres. The effect of a compensation strategy is then validated by comparing the surface mismatch value for compensated and uncompensated slots.

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1. Literature review

A number of error compensation strategies have been proposed to increase the accuracy of industrial parts machined by five-axis machine tools [1–3]. Compensation efficiency must be verified experimentally. To do so, the geometric accuracy of a machined part, before and after the implementation of the compensation, can be measured using coordinate measuring machine (CMM) and then compared. Different workpieces have been used as case studies for such purpose. Semi-spherical surfaces [4], a cone frustum as described in standard NAS979 [5] and two-dimensional contouring path [6] were proposed. In ISO10791 [7] a composite test piece in which there are some features (central hole, square, diamond, circle, sloping faces and bored holes) is introduced for accuracy check in five-axis machining centres. In the same standard, a cone frustum and a truncated square pyramid are also proposed. The machining setup and stipulations of these two artefacts were discussed and then the measurement results of the finished parts were compared in [8]. Khan and Chen [9] machined a standard workpiece with additional features like step portions, circle, diamond and cylindrical parts and also, a spherical surface to verify the compensation method effectiveness for different geometric errors. In all of the above mentioned cases, a CMM was used to inspect the machined part to compare the uncompensated and compensated part dimensions against the desired geometry. This approach requires an accurate CMM, additional setups and part handling.

Takeshima and Ihara [10] mounted an LVDT sensor on the machine tool for measuring purpose. They proposed a cubic box (containing a square hole) whose inside and outside surfaces were machined using a ball-end mill and simultaneous five-axis motion and then, measured the squareness, flatness and dimensions of the flat surfaces using only linear axes machine motion.

On-machine measurement (OMM) was used to verify the five-axis machining where a semi-sphere was machined with and without tool path compensation and then, measured with a touch probe [11]. However, the OMM accuracy needed to be compensated based on mathematical model of the machine and some diagonal measurements before the machining process.

Ibaraki et al. [12] proposed a series of simple machining patterns to identify the kinematic errors associated with rotary axes in five-axis machine tools. The geometric errors of the workpiece were measured using a CMM and then, the sensitivity of the machined part geometry to the above mentioned kinematic errors was analysed. Although the proposed method was applied solely for error identification, it illustrates the use of multiple axes

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http://dx.doi.org/10.1016/j.ijmachtools.2014.08.001
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indexations to produce related part surfaces and doing so materialize the machine volumetric errors.

In this paper, two-dimensional geometric features are milled, each using two different rotary axes indexation sets. Due to the machine geometric errors, a surface mismatch may appear in each feature that helps to verify the machine volumetric accuracy. In total, seven machining patterns are proposed to check the overall accuracy of the machine tool after compensation. There is no need for independent measurement device like a CMM as the validation process can be done using a touch probe and OMM immediately after machining. The OMM is accurate enough and does not need to be compensated since, in this case, the measurement is done in a small volume and using a single linear axis motion and in the same direction for each slot. The paper begins by presenting the mathematical model of the machine and the effect of the geometric errors using a sensitivity Jacobian in Section 2. Then, in Section 3, the surface mismatch concept and the proposed machining patterns are described while Section 4 details the machining procedure. This is followed by a sensitivity analysis of each machined pattern to the machine link geometric errors in Section 5. Section 6 presents the results followed by a discussion and conclusion in Sections 7 and 8.

2. Machine modelling

A five-axis machine tool is modelled as an open kinematic chain made of prismatic and rotary joints as shown in Fig. 1. Assuming a perfect machine, the nominal foundation frame {F} can be located at the intersection point of the two rotary axes (B and C) with its $\hat{\imath}_F$, $\hat{\jmath}_F$ and $\hat{k}_F$ directions cosines parallel to the nominal X-, Y- and Z-axis of the machine. Assuming rigid body kinematics, homogenous transformation matrices (HTMs) can be applied to model the five-axis machine tool. On a real machine, geometric errors occur as link error affecting the position and orientation of each axis with respect to its predecessor in the chain. So, for example, the Z-axis HTM, ${}^{F}T_{Z}$ can be decomposed as a nominal link ${}^{F}T_{Z_0}$, a link error ${}^{Z_0}T_{Z_0'}$, and a nominal motion ${}^{Z_0{}'}T_{Z}$, so that

$$ {}^{F}T_{Z} = {}^{F}T_{Z_0}\,{}^{Z_0}T_{Z_0'}\,{}^{Z0'}T_{Z} \tag{1} $$

where F is the foundation frame, Z_0 is the nominal joint frame, Z_0' is the actual joint frame before motion and Z is the joint frame after nominal motion.

Assuming small errors, a small angle approximation ($\sin\theta \approx \theta$, $\cos\theta \approx 1$) is used and a linear relationship results between small changes in machine link errors and the consequent variations in feature-tool relative location. A nominal Jacobian matrix is generated that expresses the effect of the link geometric errors (E_{p}) on differential changes in volumetric errors at the tool tip relative to feature frame projected in the tool frame [13,14]

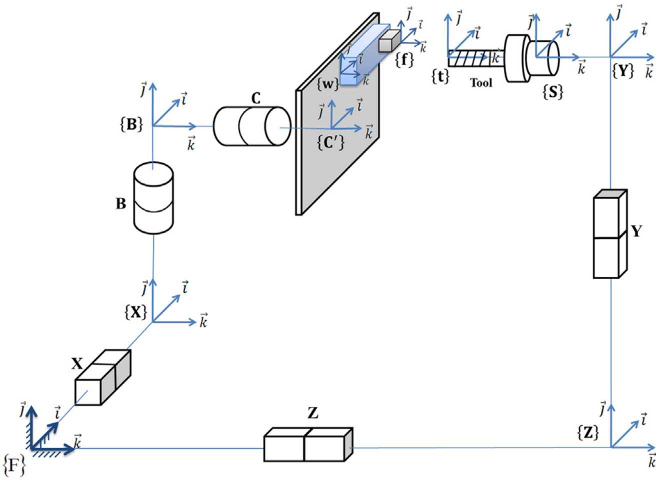

Fig. 1. Five-axis machine tool (WCBXFZYSt) as a kinematic chain.

$$ {}^{\{t\},f}E_{V_{\mathrm{t}}} = {}^{\{t\},f}J_{t}\,E_{\mathrm{p}} \tag{2} $$

where ${}^{\{t\},f}E_{V_{\mathrm{t}}}$ is the 6×1 volumetric error twist of the tool (subscript t) relative to the feature (f) expressed in tool frame, {t}, and has six error components, $[E_{\mathrm{XV}}\ E_{\mathrm{YV}}\ E_{\mathrm{ZV}}\ E_{\mathrm{AV}}\ E_{\mathrm{BV}}\ E_{\mathrm{CV}}]^{\mathrm{T}}$.

According to Abbaszadeh-Mir et al. [13] and ISO-231 standard [15], only eight machine error parameters are sufficient to fully characterise a five-axis machine tool link errors. So, in this paper, only these eight components are considered

$$ E_{\mathrm{p}} = [E_{\mathrm{AOB}}\ E_{\mathrm{COB}}\ \ E_{\mathrm{XOC}}\ \ E_{\mathrm{AOC}}\ E_{\mathrm{BOC}}\ E_{\mathrm{BOZ}}\ E_{\mathrm{AOY}}\ \ E_{\mathrm{COY}}]^{T} \tag{3} $$

The error notations are based on ISO230-1[15].

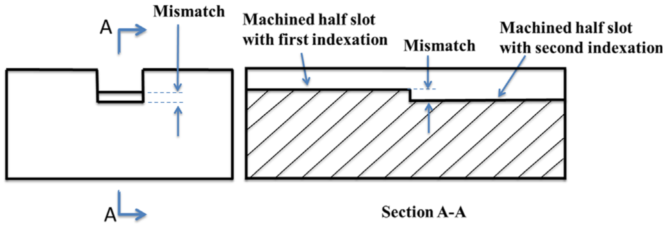

Fig. 2. Depth mismatch between two halves of the machined slot.

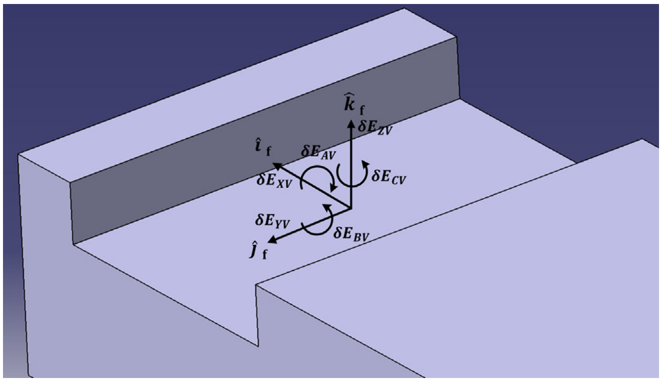

Fig. 3. Coordinate system and error components on the machined slot.

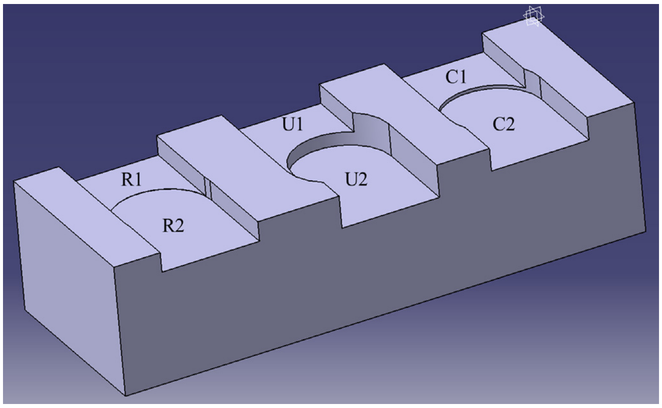

Fig. 4. Reference (R), uncompensated (U) and compensated (C) machined slots in each pattern.

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